

Development in Laser Peening of Advanced Ceramic

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ABSTRACT

Laser peening is a well-known process applicable to surface treat metals and alloys in various industrial sectors. Research in the area of laser peening of ceramics is still scarce and a complete laser-ceramic interaction is still unreported. This paper focuses on laser peening of Al₂O₃ ceramics employed for cutting tools, armor plating, dental and biomedical implants, with a view to elucidate the unreported work. A detailed investigation was conducted with 1064nm Nd:YAG ns pulse laser to first understand the surface effects, namely: the topography, hardness, K_{1c} and the microstructure of Al₂O₃ advanced ceramics. The results showed changes in surface roughness and microstructural modification after laser peening. An increase in surface hardness was found by almost 2 folds, as the diamond footprints and its flaws sizes were considerably reduced, thus, enhancing the resistance of Al₂O₃ to better withstand mechanical impact. This inherently led to an enhancement in the K_{1c} by about 42%. This is attributed to an induction of compressive residual stress and phase transformation. This work is a first-step towards the development of a 3-dimensional laser peening technique to surface treat many advanced ceramic components. This work has shown that upon tailoring the laser peening parameters may directly control ceramic topography, microstructure, hardness and the K_{1c}. This is useful for increasing the performance of ceramics particularly for demanding applications particularly where it matters. Upon successful peening of bullet proof vests could result to higher ballistic strength and resistance against higher sonic velocity, which would not only prevent serious injuries, but could also help to save lives of soldiers on the battle fields.

Keywords: Laser Peening, Al₂O₃, Ceramics, Hardness, K_{1c}, Microstructure, Surface finish

1. INTRODUCTION

Research rationale

Surface treatment of metals and alloys by laser peening has been a successful technique for a number of years¹⁻⁴. This is due to the benefits obtained by laser peening of metal/alloys in particular. The advantages offered by the process are, namely: increased residual compressive stress, reduction in frictional properties, wear rate, enhanced surface finish and hardness. However, laser peening of advanced ceramics is still under-developed and scarce. This is because of their physical characteristics that prevent them from behaving in the same way as metals, especially, when exposed to short pulses of laser energy. In particular, it is difficult to bring about mechanical yielding and plastics deformation within ceramics. Therefore, it is difficult to gain any beneficial effects which are conventionally obtained on metals. As such, it is of a great interest to investigate the effects of laser peening on the advanced ceramics. Upon success, would first open new avenues for the use of ceramics in demanding applications, such as for ceramic armor plating and in conditions where high level of mechanical and thermal stress as well as in presence of a corrosive environment. Typical ceramic products in engineering such as high performance cutting tools namely: cutting knives, and machine tools could also benefit from laser peening. Secondly, this study would also enable one to understand the effects of the pulsed laser energy interaction with advanced ceramics such as alumina. Much work has been conducted in the area of laser peening of metallic parts⁵⁻⁶. Recent published work in this area has also evolved from the use of microsecond, nanosecond to shorter pulses being applied at both picosecond and femtosecond range on metals⁷⁻¹¹. With that said, the only previous investigation that closely relates to the work in this study is that of Akita *et.al.*¹². The work in their investigation involved the use of a Nd:YAG laser (532nm wavelength) to peen a Si₃N₄ ceramics. They reported that plastic straining on the surface layer resulted to induction of compressive residual stress, with an increase in surface roughness, and an enhancement in bending stress. Having said

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that, the research herein is still very important because the reporting's made by Akita *et.al* were first, only, for a Si_3N_4 ceramic. Also, an important property such as hardness, K_{Ic} , or microstructural modification was not examined to verify the residual stress within the surface and the subsurface. Moreover, no evidence of a material integrity was reported. This work is a first-step towards developing a laser peening process of ceramics and to understand the effects of laser peening from a physical characteristics, namely: surface topography; hardness; fracture toughness parameter K_{Ic} ; residual stress and the microstructure of the laser peened Al_2O_3 , to not only fill the gap in knowledge but with a view to provide a strengthening technique for enhancing the service life of various ceramic components.

Laser Peening Fundamentals

Technically, effective laser peening of materials depends on the introduction of a plasma produced during laser-material interaction. In most instances, this is created by supplying a thin layer of water on to the work-piece as shown in Figure 1. The plasma enables the absorption of the radiated laser energy to create sufficient pressure that is generally measured in 100s of atmospheres^{6-10,13}. Thus, the local distribution of high energy is further absorbed into the material and produces a circular indentation, depending on the shape of the laser beam. The incident laser energy and the generated plasma, consequently, produces sufficient level of shock-wave within the surface and the sub-surface of the material. This creates thermal expansion into the material and deems the material under compression within the laser affected region. The laser peening process requires precise control and the induction of correct energy density. Over peening may result to generation of tensile stresses or the possibility of drilling into the material which defeats the objective. Typically, laser beam absorption also depends on the particular wavelength applied at the material surface. Particularly for ceramics, laser in the range of $1\mu\text{m}$ wavelength and under, tends to produce sufficient absorption¹⁴⁻¹⁷.

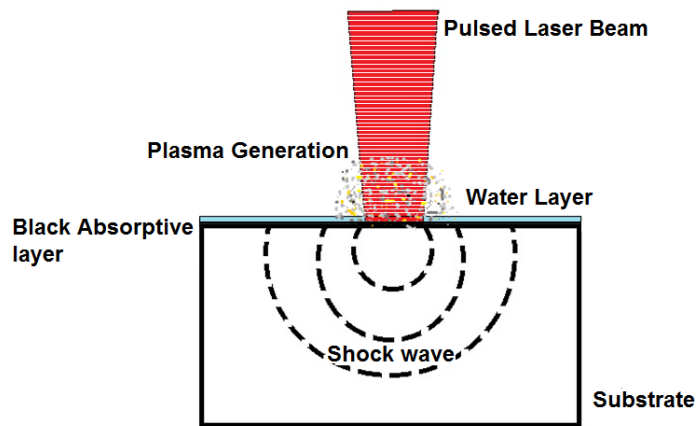


Figure 1 A schematic showing the features involved in effective laser peening of materials in general.

2. EXPERIMENTATION AND METHODOLOGY

A cold isostatically pressed (CIPed) Al_2O_3 advanced ceramic was used as an experimental material from Shanghai Unite Technology (Shanghai, China) with the dimension 50mm x 10mm x 5mm bar as shown in Figure 2(a). The advanced Al_2O_3 ceramic comprised of 99.5 % Al_2O_3 and 0.5 % unspecified CIPed at 455 bar pressure from all of its orientations and sintered at 1200°C for 5 hours (as specified by the manufacturer). The ceramic was mechanically and microstructurally characterized prior to all experimentation. The average as-received surface finish (from 5 samples) was $R_a 1.53\mu\text{m}$. The surface hardness was measured to be 1276 HV and a plane strain fracture toughness (K_{Ic}) was determined as $2.31 \text{ MPa}\cdot\text{m}^{1/2}$.

The laser used in this investigation was a pulsed Nd:YAG laser (Continuum; Powerlite; DLS 8000; San Jose; USA) as shown in Figure 2. This emitted a 1064nm wavelength with laser energy applied ranging from a minimum of 30mJ to a maximum of 966 mJ. Thereafter, the effects were examined using an optical microscope and an SEM (see Figure 2(d) for details). A pulse repetition rate (PRR) of 10Hz and a pulse duration of 6ns was delivered as a single shot to the surface of the Al_2O_3 . The laser beam comprised of a flat-top profile and a divergence angle of 0.45mrad. As this was a first step-study, the laser beam was simply delivered with a raw laser spot diameter of 9.5 mm and was sufficient to affect the ceramic due to its low divergence and high brightness. No assist gas was used for the laser peening. In addition, laser peening is often conducted using an absorptive surface layer over the material and is also a water assisted technique^{12, 14}.

The work herein, have employed the laser alone technique as the absorptive layer could melt and adhere to the ceramic and water assisted peening and laser alone peening both warrant individual investigations. However, our future investigations involve the use of such techniques to understand their individual effects respectively. Five samples were used for the experiments in order to evaluate the effect of laser peening on the Al_2O_3 . Laser energy was recorded using an energy meter which enabled to measure the energy fluctuations of $\pm 3\text{mJ}$, recorder for 30 sec duration. Figure 2(b) show a footprint of the 9.5 mm spot on a laser burn paper prior to conducting the main experiments and Figure 2(c) shows the effects in varying the laser energy on the Al_2O_3 advanced ceramic. Surface finish and topography was examined using a chromatic confocal imaging device (3-D Surface Profiler; Micromasure 2; Polytec Ltd; Hertfordshire; England). Vickers indentation tests were carried out with 7.5Kg indentation load (VHTM 2000; Vickers Ltd. Engineering Group; Sheffield; England). All crack lengths were observed using an optical microscopy and scanning electron microscope (SEM) by Leo-1455VP; Cambridge, England. Fracture toughness parameter K_{Ic} was determined based on the methodology in our previous publication¹⁵.

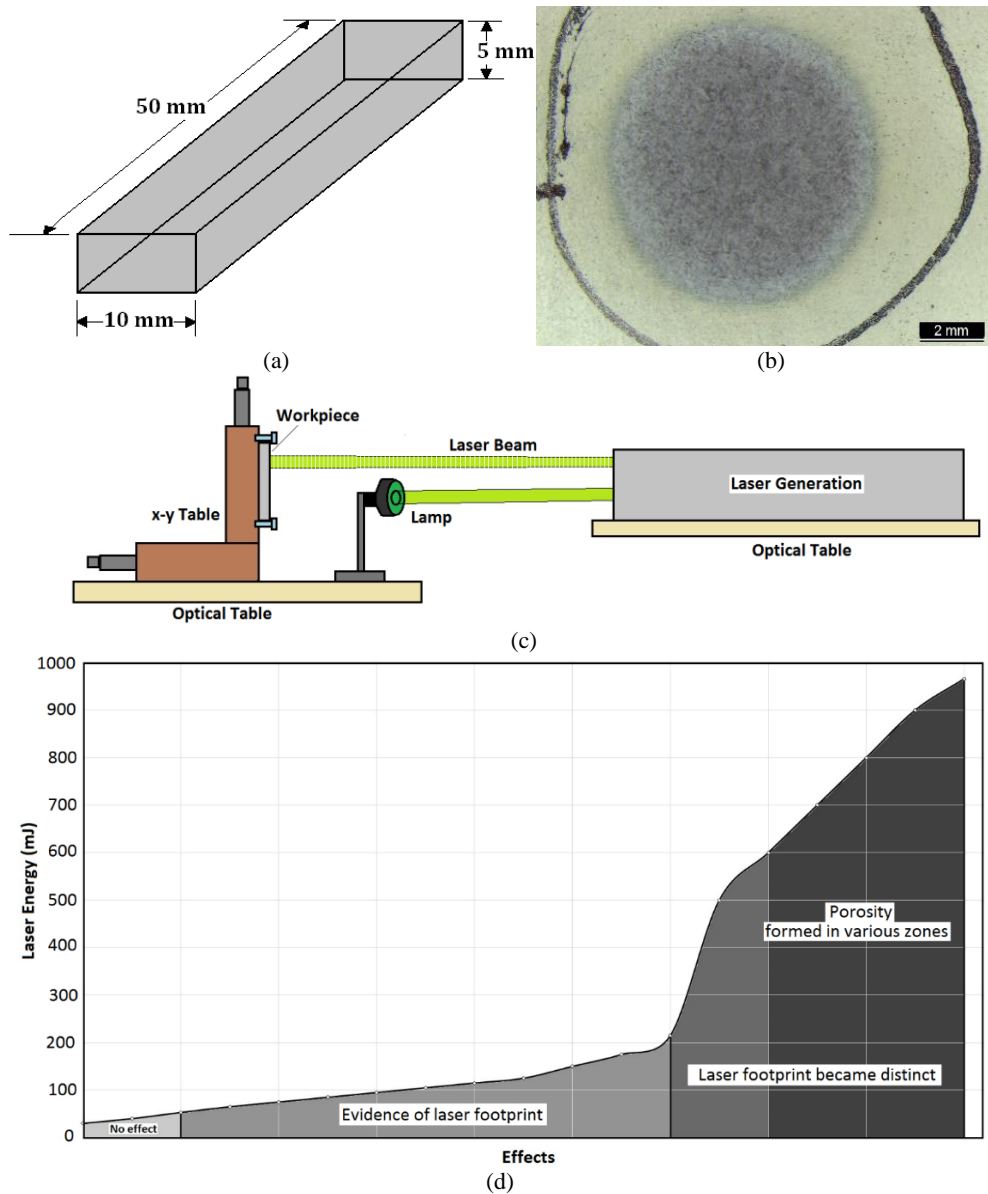


Figure 2. A schematic of the Al_2O_3 advanced ceramic work-piece in (a); an optical image of the 8.5mm laser beam foot-print at 966 mJ, 10Hz PRR, for 6ns pulse duration, directed on a burn paper shown at x100 resolution in (b); the experimental set-up in (c); and (d) a graphical representation of the surface effects with respect to increase in laser energy.

3. RESULTS AND DISCUSSION

Topography

All surface measurements were conducted over 3 individual sample of Al_2O_3 each condition. The arithmetic mean deviation of the surface roughness profile (R_a) was measured to be $1.53\mu\text{m}$ for the as-received Al_2O_3 . Comparatively, the average R_a value for the laser peened surfaces were up to and in some instances over, by 3 folds, as shown in Table 1 and Figure 3(a) to (d). This is generally expected with laser peening of metallic materials and could also be predicted/tailored, based on the material removal phenomena during laser pulse processing. What is interesting is that the surface roughness and material removal decreased with increasing applied laser energy. Generally, ablation rates are thought to be higher with increase in laser energy removing material through vaporization¹⁸. Thus, increases the roughness through higher material removal rate. This was however, not the case herein. Based on the difference in our results in comparison to the conventional effects that take place during laser peening of metals, the decreasing surface roughness with increasing laser energy was attributed to the removal of machined striations that were present over the Al_2O_3 advanced ceramic. A considerable level of machining marks were initially present in the as-received surface (refer to microstructural study) that were eliminated after laser peening. This in turn deemed the laser surface to become smoother at 966mJ compared to the surface laser peened at 216mJ and 600mJ.

Table 1. Showing the average surface roughness of the Al_2O_3 as-received surface and the laser peened surfaces.

Surfaces	Surface Roughness (R_a)
As-received	$1.53\mu\text{m}$
Laser Peened (215 mJ)	$5.27\mu\text{m}$
Laser Peened (600 mJ)	$4.37\mu\text{m}$
Laser Peened (966 mJ)	$3.52\mu\text{m}$

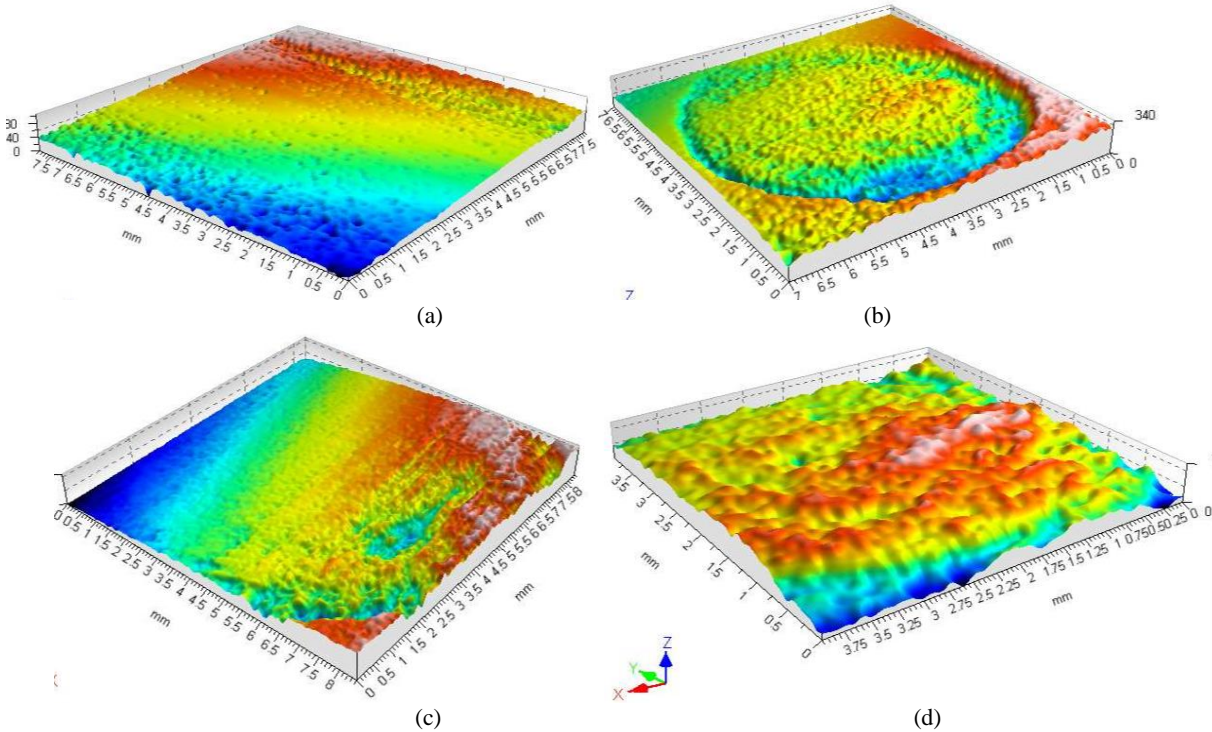


Figure 3. Surface profile images of the Al_2O_3 as-received surface in (a); and the laser peened surface applied with 215 mJ in (b); 600 mJ in (c); and 966 mJ in (d).

Microstructural Modification

Figure 4(a) and (b) shows an optical image of the 8.5 mm diameter laser spot. With increasing power the spot diameter becomes more evident on the surface of the Al_2O_3 . Using higher laser power in the range of 800mJ to 966mJ, it was possible to see the maximum footprint of the beam. Figure 5(a) illustrates the optical images of the as-received surface in (a) and the laser peened surface in (b) to (d) with increasing laser power, whilst the repetition rate, spot size and the pulse duration were kept constant to 10Hz, 8.5 mm and 6ns. As evident from the optical images, the by increasing the laser energy, the effect on the Al_2O_3 ceramic become somewhat distinct. This is particularly evident when the laser treated surfaces were compared to the as-received surface. The as-received surface in some areas showed evidence of machining marks such as striations, and micro-pores (also later evident from the SEM images). With increasing laser energy, the machining marks and striations were no longer apparent and the laser energy showed increasing level of ablation over the laser irradiated zone. Particularly at 850mJ and 966mJ resulted to enough ablation, which in turn, opened some surface pores.

The SEM micrographs in Figure 6(a) to (d) also confirm that the increasing laser energy created a significant change to the microstructure. At 215mJ, significant level of microstructural change is not apparent. However, one can see that elimination of pre-existing features at 600mJ and were further distinctive at 966mJ in Figure 6(c) and (d). Having said that, opening of pores and voids at the maximum laser energy could be attributed to the laser pulse ablating some of the material and exposing the surface defects. This goes to show that undesirable feature and surface free from defects can be readily obtained using laser peening energy around 600mJ at the applied conditions. In terms of investigating the grain boundaries, the ceramic is required to be etched by chemical or thermal means so that the grains boundary conditions prior to and after laser peening could be examined in detail.

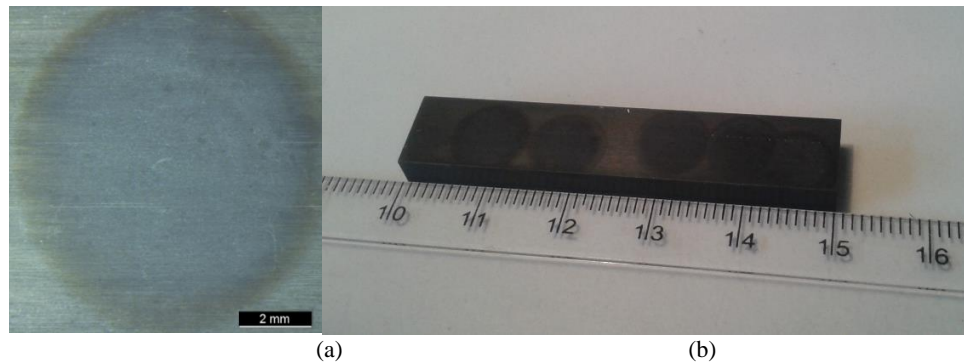
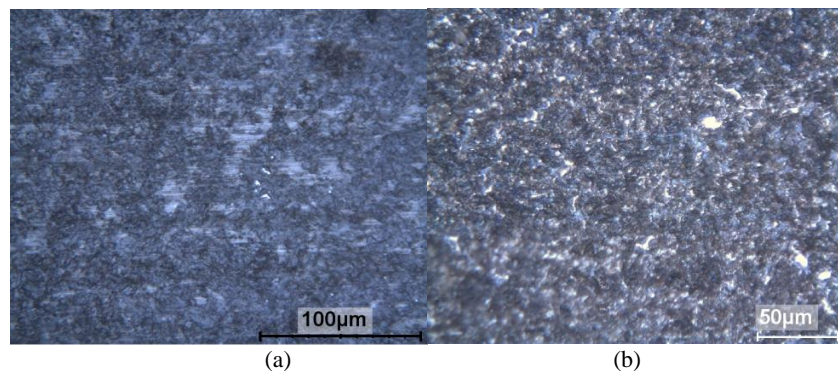


Figure 4. Optical images of the laser peened surface of Al_2O_3 advanced ceramic laser peened at 966 mJ, 10Hz, for 6ns pulse duration with a single pulse in (a); and the actual workpiece with distributed peening in (b).



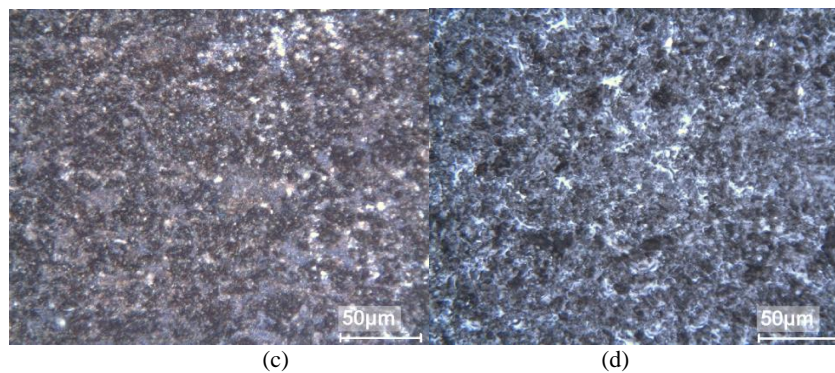


Figure 5. Optical images of the Al_2O_3 as-received surface in (a); Al_2O_3 surface irradiated at 215mJ in (b); Al_2O_3 surface irradiated at 600mJ in (c); and Al_2O_3 surface irradiated at 966mJ in (d) at 8.5mm spot size, using pulse duration of 6ns and 10Hz PRR shown at x50 resolution.

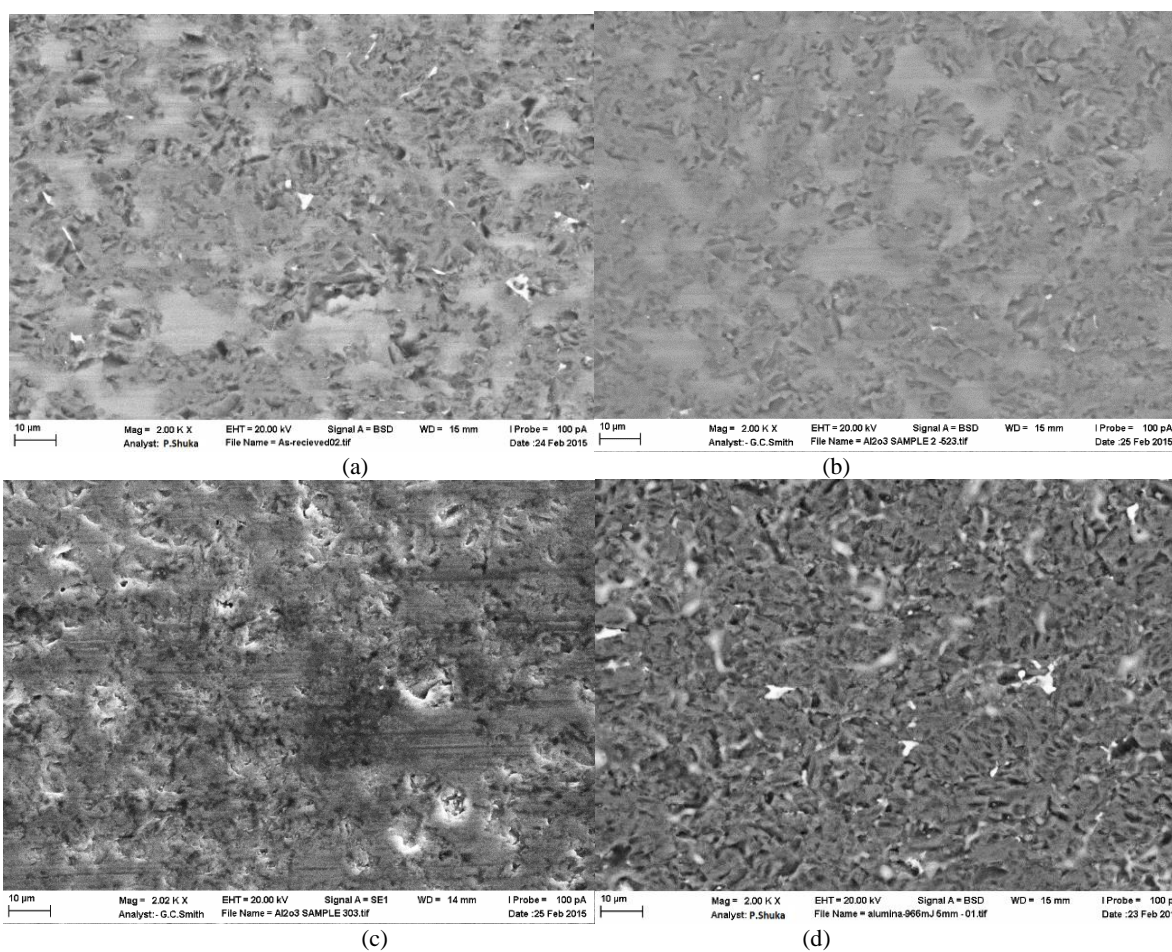


Figure 6 SEM image of the Al_2O_3 as-received surface in (a), Al_2O_3 surface laser peened at 215mJ in (b); peened at 600mJ in (c); and 966mJ in (d).

Indentation Response, Flaw Size, Hardness and Fracture Toughness Parameter – K_{Ic}

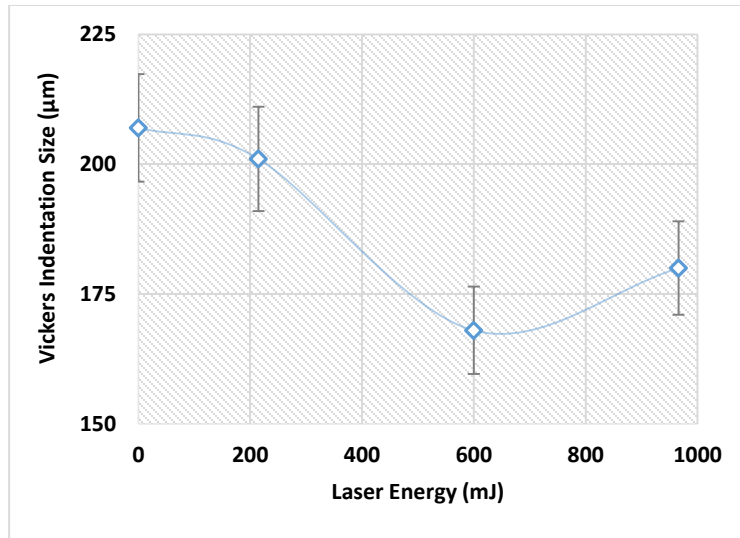
Hardness measurements using the Vickers indentation technique showed that the starting as-received samples comprised of surface hardness of 1276HV from an average of 10 indentations tests. At the same time, the size of the Vickers diamond footprint was measured to be $212\mu\text{m}$ and the respective flaw size (from the edge of the diamond) were measured to be $217\mu\text{m}$ as shown in Figure 7(a) and (b). An increase in laser energy showed that the Vickers diamond footprints began to reduce by an average of $12\mu\text{m}$ at 215mJ, $44\mu\text{m}$ at 600mJ and finally at $32\mu\text{m}$ for 966mJ of irradiation. But, in general, the results showed that laser peening increased the surface hardness in comparison to the as-received surface.

Furthermore, the flaw size for the diamond indents created on the laser peened surface were also smaller in comparison to the as-received surface. This indicated that the surface became less prone to cracking and showed resistance against mechanical impact despite the measured hardness to have shown significant rise, thus, increasing the brittleness. The Vickers diamond footprints also reduced in size considerably indicating that harder surface responded less in comparison to the softer surface during the Vickers indentation test. The hardness of the laser peened surfaces was measured to a maximum of 2037HV at 600mJ and then 1677HV at 966mJ as shown in Figure 7(c). Therefore, our interest in terms of future studies in this area may focus on the rationale for the change in hardness from 2037HV to 1677HV at 600mJ and 966mJ respectively. Albeit, the results in comparison to the as-received surface have clearly demonstrated a level of strengthening of the Al_2O_3 advanced ceramic as it has become less prone to cracking and has shown a good response to Vickers indentation load impact of 7.5Kg.

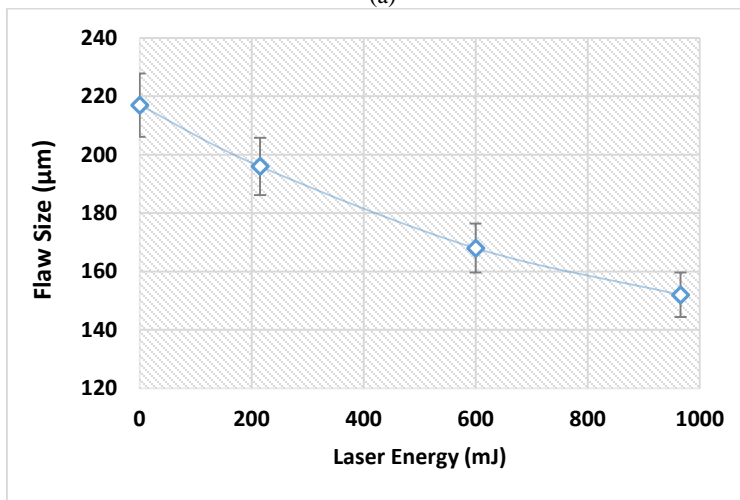
Furthermore, modification of the fracture toughness parameter K_{Ic} is presented in Figure 7(d). The graph demonstrate an increase in K_{Ic} from $2.32 \text{ MPa m}^{1/2}$ (as-received surface) at 0mJ to $2.60 \text{ MPa m}^{1/2}$ at 215mJ and $3.29 \text{ MPa m}^{1/2}$ at 966 mJ respectively for the Al_2O_3 advanced ceramics. This revealed that the hardness, the respective flaw sizes and the K_{Ic} could be tailored to suite a specific industrial need by optimizing the laser energy and the associated parameters in general.

Nonetheless, the surface hardening and the increasing fracture toughness could be attributed to an increase in residual stress compressive stress layer during laser peening. This compressive stress layer may form if dislocation motion was increased through plastic deformation at sub-micron level which then results to better indentation response under mechanical loading. Thus, resulting to less flaws on the diamond footprint as the acting tensile stress of the Vickers indenter must overcome the induced compressive stress under the laser peened area. Further analysis of the residual stress state under the laser peened spot, and through its cross-section should therefore be undertaken in future as this is generally an important aspect of both the mechanical and laser peening processes.

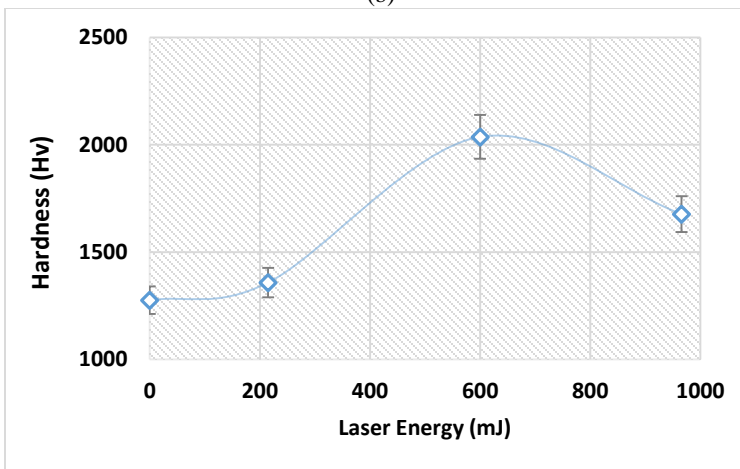
On this more, it is also postulated that surface strengthening resulted from a phase transformation of the Al_2O_3 , whereby the alumina starting phase M+C (mullite + cristobalite) would have transformed to a mullite (M) phase, or alternatively, depending on the laser induced temperature, a phase change of A+M (alumina + silicon dioxide) comprising of superior hardness and indentation response than the starting as-received surface of the Al_2O_3 . In any case, the leading author of this paper suggests a full residual stress state and a phase transformation examination for deeper understanding of laser peening advanced ceramics.



(a)



(b)



(c)

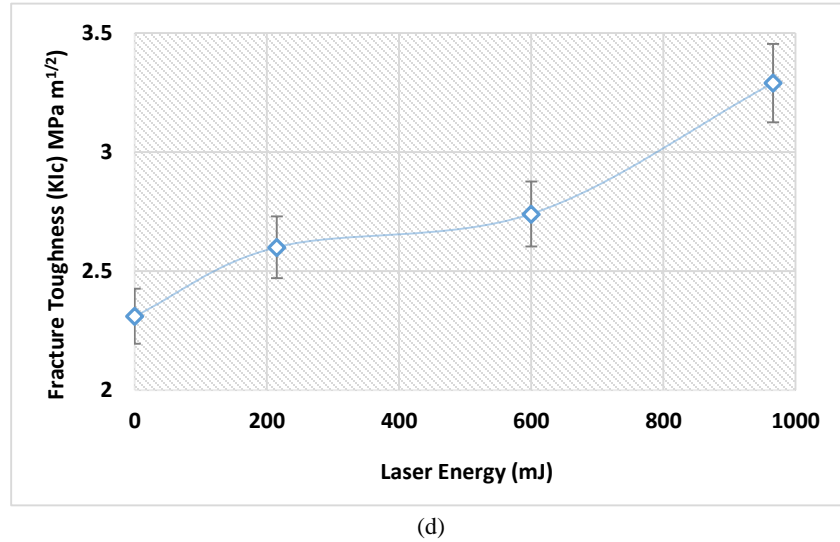


Figure 7. Graphical illustration showing Vickers indentation size in (a); change in hardness in (b); change in Vickers indentation induced flaw size in (c); and (d) the fracture toughness parameter K_{Ic} for both the at as-received (0mJ) and the laser peened surfaces of the Al_2O_3 advanced ceramics.

4. CONCLUSSIONS

Laser peening of Al_2O_3 advanced ceramics was reported in this study for the first time. This is a first-step towards the development of a 3-dimentional laser peening process of many advanced ceramic components in various industrial sectors. The results herein have shown that it is possible to tailor the ceramic topography, microstructure, hardness and the K_{Ic} by inducing the required laser energy and associated laser parameters. This in turn could prove to be useful for increasing the performance of ceramics used for cutting tools; dental implants; tappet valves and pistons for automotive engines. Laser peening of ceramics could matter in particular for demanding applications such as for the surface treatment of armor plating, whereby, a successfully peening of bullet proof vest could result to higher ballistic strength and resistance against higher sonic velocity. This may not only prevent serious injuries, but could also help to save lives of soldiers on the battle fields. The results of this work demonstrate the following outcome:

1. Increase in surface roughness in comparison to the as-received surface. However, with increasing laser energy, the surface roughness reduced. This indicated that a level of melting and solidification at sub-micron level may have took place at the highest applied laser energy.
2. Considerable microstructural modification also resulted on the laser peened surfaces as the pre-existing surface defects were eliminated with increasing laser power, but surface pores and voids were exposed at the highest laser energy applied in various areas of the Al_2O_3 samples.
3. Hardness was increased from 1276HV to 2037HV on the laser irradiation zone at 600mJ, whilst the hardness reduced to 1677HV at 966mJ of applied laser energy. Nonetheless, all laser peened surfaces showed increase in hardness and reduction in the diamond footprints from the Vickers indentation test. Moreover, the flaw size of the diamond footprints were also reduced which goes to show that the laser peened Al_2O_3 responded better under mechanical loading in comparison to the as-received sample.
4. Increase in fracture toughness also resulted after laser peening from 2.32 MPa $m^{1/2}$ to a 3.29 MPa $m^{1/2}$ for the applied conditions. Both the increase in hardness, a reduction in the flaw size and the increase in the surface K_{Ic} indicated that the laser peened surface may have undergone a level of plastic deformation. This in turn, generated a compressive stress layer under the peened area and so, prevented a deeper and broader penetration of the diamond footprint and expansion of the resulting crack lengths.

In addition, the leading author of this paper further suggest a full residual stress analysis and phase transformation study to understand the laser material interaction during laser peening.

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